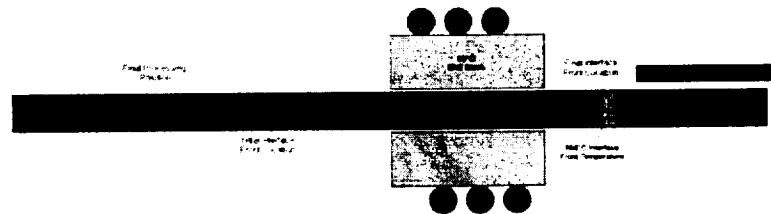


Quench Module Insert (QMI)

Microgravity Materials Processing

- *What is microgravity materials processing?*
 - *Creating desired thermal gradient and solid/liquid interface front movement for a given processing temperature in a microgravity environment*



- The science requirements for materials processing is to provide the desired PI requirements of thermal gradient, solid/liquid interface front velocity for a given processing temperature desired by the PI.
- Processing is performed by translating the furnace with the sample in a stationary position to minimize any disturbances to the solid/liquid interface front during steady state processing.
- Typical sample materials for this metals and alloys furnace are: lead-tin alloys, lead-antimony alloys, and aluminum alloys
- Samples must be safe to process and therefore typically are contained with hermetically sealed cartridge tubes (gas tight) with inner ceramic liners (liquid tight) to prevent contamination and/or reaction of the sample material with the cartridge tube.

Thermal Design, Analysis, and Testing of the Quench Module Insert Bread Board

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Quench Module Insert (QMI)

Science Requirements

- *Metals and Alloys Processing*
 - *Currently Supporting Two Investigators*
 - *Sample Processing from 600°C to 1400°C*
 - *Various Sample Materials up to 1cm diameter*
 - *Sample Gradients up to 150°C/cm for a 1cm aluminum sample at 1100°C processing*
 - *Sample Isothermality of $\pm 10^\circ\text{C}$ over a 10cm length of a 1cm dia. aluminum sample*
 - *20cm hot zone; four independently controlled zones; 20cm of translation; approximately 18cm of sample processing*
 - *Sample Quench rates providing solidification of a 2cm length of a 1cm diameter aluminum sample in 2seconds*

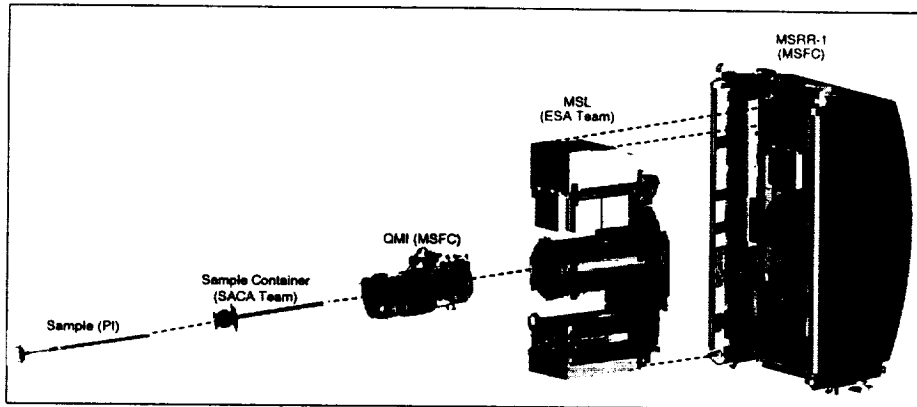
•QMI currently supports:

•Dr. Doru Stefanescu/University of Alabama; “Particles Engulfment and Pushing by Solidifying Interfaces (PEP)”; Aluminum-based alloys which are cast with Zirconia particles to study the effects of temperature gradient, sample characteristics, particle size, and interface front velocity on the process of engulfing or pushing these particles at the solid/liquid interface location. Typical requirements denoted are: 900°C processing, 100°C/cm sample gradient, ? processing velocities, and a rapid quench rate of 100°C/sec at the end of processing.

•Dr. Barry Andrews/University of Alabama at Birmingham; “Coupled Growth in Hypermonotectics (CGH)”; Aluminum-Indium alloys (immiscible) processed in a microgravity environment to investigate the effects of alloying percentages, thermal gradient, and interface front velocity on the process of forming indium fibers within an aluminum matrix. Typical requirements denoted are: 1100°C processing, 150°C/cm sample gradient, and ? processing velocities.

•QMI has been and is currently being studied to support other investigations in the areas of metals/alloys processing and semi-conductor crystal growth. The flexibility of the cold zone design and the independent control of the four heated zones provides QMI with a flexible design that can be used by many investigations.

Quench Module Insert (QMI) Interfaces



- The MSRR-1 rack is a full rack system supported by MSFC. The MSRR-1 rack provides station resources (power, cooling, command and control) to payloads.
- The right portion of the MSRR-1 rack is used by the MSL (ESA) system.
- The MSL system provides all of the interfacing hardware to the various inserts (power, cooling, data acquisition, control, house keeping, temperature monitoring/control, etc.)
- The QMI uses the resources provided by the MSL system to attain the science requirements denoted by the Principle Investigators and their investigations.
- The Sample Container (SACA) uses the environments generated by the QMI to attain science requirements and processing conditions denoted by the PIs.
- The samples are fabricated by the PIs to focus on the science aspects of their investigations.
- The systems must work in harmony and interface with each other properly. This results in a lot of interface documentation, specifications, and design impacts which are flowed down from the Station level to the PI level of this intricate system. Safety of the entire system must be coordinated at all levels.

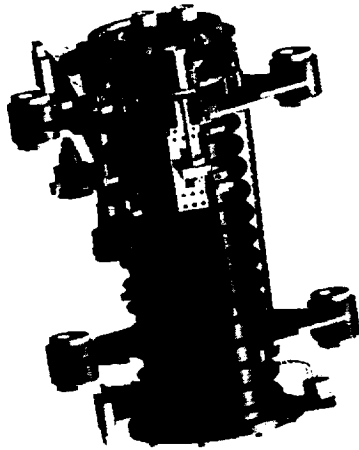
Quench Module Insert (QMI)

Interface Requirements

- *Integration in the ESA's Materials Science Laboratory*
 - *3kW Max. Power/Cooling Allocation (currently showing a max. power requirement of less than 450W at 1400°C)*
 - *Fail Safe Loss of Cooling (max. 600ml of expelled volume)*
 - *Touch Temperature (>49°C) during all phases of processing*
 - *Limits on waste heat losses to the ESA thermal chamber (100W)*
 - *Max. Shell temperatures*
 - *Max. Coolant return temperatures*
 - *190mbar pressure drop at max. coolant flow conditions*

- Various interface agreements and specifications are used to denote requirements and allocations at all levels of the system.
- QMI's major requirements to the ESA (MSL) system are in the areas of resource allocation (power, cooling), command/control, and safety.

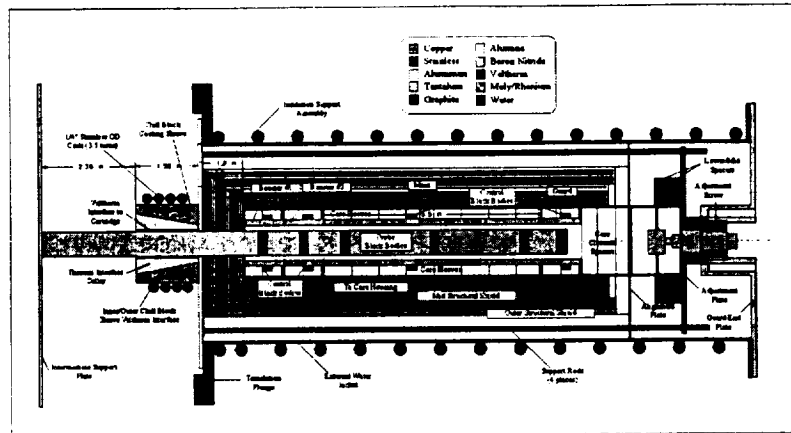
Quench Module Insert (QMI) Design Layout



- *Bridgman-type, Vacuum Furnace*
- *Four heated zones*
- *One interchangeable cold zone*
- *Phase Change Quench System*
- *Highly Efficient Insulation Design*

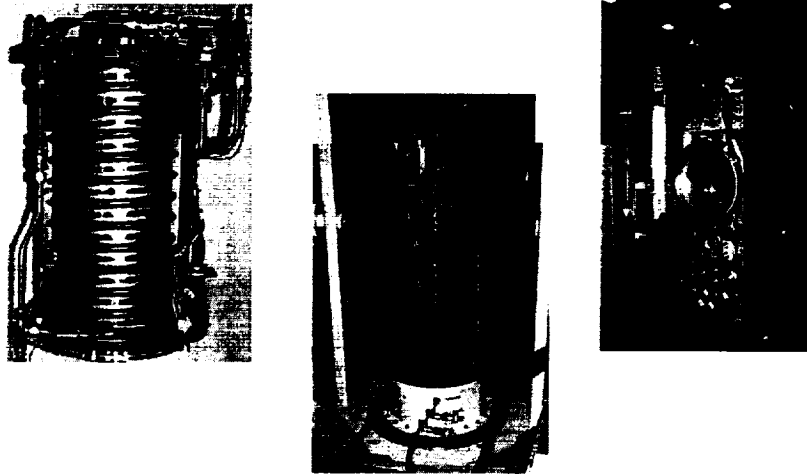
- QMI is a Bridgman-style furnace capable of providing up to a 1400°C processing environment.
- There are four heated zones (two booster heaters, one main heater, and one guard)
- The dual boosters were required by Dr. Stefanescu's investigation to maximize the capability of producing a high thermal gradient without exceeding a maximum processing temperature of 900°C. These zones typically use set points 50-150°C higher in temperature than the sample processing temperature to induce large thermal gradients in the sample.
- The main heater is used to stabilize and/or set the processing temperature of the sample.
- The guard heater provides a measure of preventing hot zone temperature roll off at the end of the sample cartridge.
- The cold zone is interchangeable which allows cartridge sizes to be varied as per PI science requirements. This enables the QMI design the flexibility to tailor the needs of the investigator to extract heat at a desired rate thereby allowing better control of the interface front position.
- The phase change quench system provides extremely fast sample cooling. Current benchtop testing has shown that the PCD (Phase Change Device) provides quench rates that have been unattainable by water-based or gas-based systems previously used. The design also has very little interface or resource requirements from the MSL system.
- The QMI insulation system has been shown by testing to be highly efficient. The design minimizes contaminant materials (outgassing sources) and is very

Quench Module Insert (QMI) Design Layout



- The layout of the QMI is shown in this figure.
- The four heated zones are shown along with their control black bodies which are used to monitor zone temperatures and provide excellent temperature control of the system. The responsiveness of these black bodies will assure that there are no interface front disturbances caused by erratic hot zone control during steady state processing. These control black bodies also provide a redundant measurement of the zone temperatures to assure adequate life and repeatability of the system. The zones are insulated from one another by foil insulation to allow for better control temperature setpoint offsets between the boosters and the main heater thereby increasing the thermal gradient generation capability of the QMI.
- The gradient zone is comprised of many layers of axial insulation to prevent axial heat loss from the booster #1 heater and to minimize heat transfer/loss from the sample cartridge in the gradient zone. The core closeout spacers and the lower/mid spacers provide conductive breaks in the heat flow path on the guard end of the core to minimize heat loss to the adjustment plate portion of the insert.
- The cone-shaped chill block is comprised of an outer chill block cooling sleeve instrumented for control of the cold zone via flow rate variation. The inner chill block sleeve (thermal interface collar) interfaces with the outer sleeve via a interface filler material to assure proper conductive coupling of the inner sleeve with the outer sleeve with a minimal contact force (10lb). The inner sleeve is lined with a graphite fiber interface material called Veltherm at the cold zone-to-chill block interface to conductively extract heat from the cartridge while maintaining a conformal interface.

Quench Module Insert (QMI) Design Layout



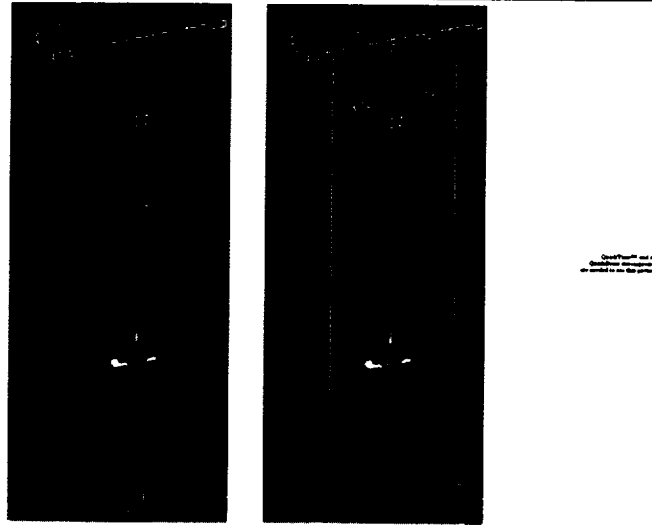
- The far left figure shows the current QMI bread board. The external water jacket along with its cooling coils are shown. The chill block is somewhat visible on the top of the unit. Various control and health/status instrumentation along with the water loop routing are shown.
- The middle figure shows the QMI bread board mounted within it's processing canister. This bread board system contains all of the equipment required to mimic the ESA MSL system (cooling cart, translation, temperature control, power supplies, etc.). The unit is housed in the Microgravity Design Laboratory at MSFC.
- The far right figure is a small scale mock up of the integrated MSRR-1 rack system. The left portion of the rack shows the integration of ESA's MSL system with a typical insert and cartridge. The thermal chamber of the MSL system is not shown to provide insight into the integration of the cartridge, insert, and facility.

QMI Thermal Analysis and Design Methodology

- *Modeling via TRASYS II, SINDA/G, and SINDA85*
 - *One overall axi-symmetric SINDA/G model (>5000 nodes) per Unit*
 - *Easily reconfigured for any translation position via user constants*
 - *Detailed component level temperature summary tables and plots generated for each case*
 - *User defined sinroutines for helical heat transfer coefficient, uniform power distribution, summary tables, plot files*
 - *Three TRASYS II models (translatable bore, jacket, and PCD)*
 - *Easily reconfigured for any translation position or SACA geometry/surface properties via users constants*
- *Preliminary Hot Zone Test Article to verify insulation and thermal performance in a static test condition (heavily instrumented)*
- *Hot Zone Test Article model correlation results and lessons learned are applied to Bread Board and Flight models*
- *Bread Board model correlation results and lessons learned are applied to both the Bread Board and Flight models*

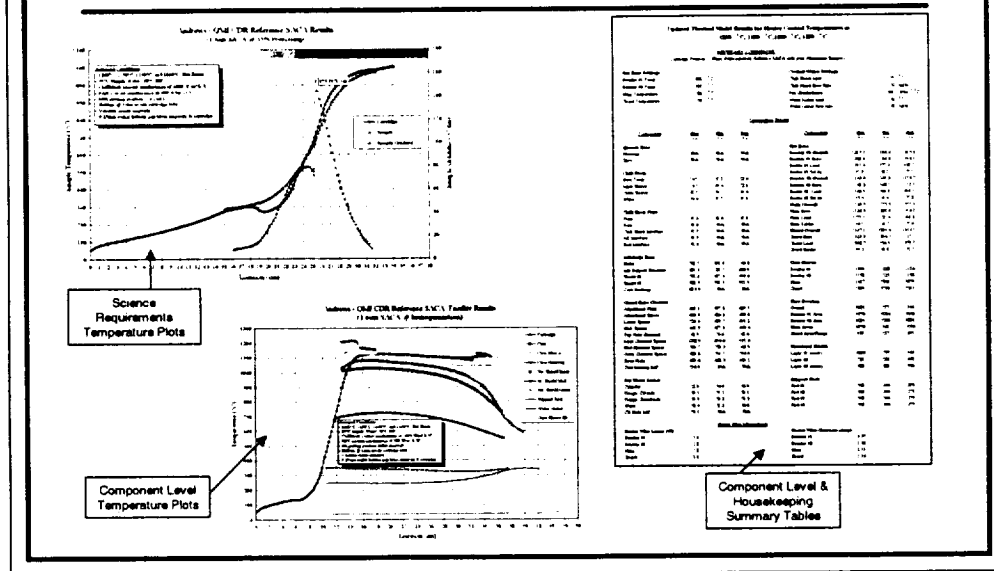
- The tools used for the QMI design consisted of standard thermal modeling methods using SINDAG and SINDA85, with various TRASYS models to obtain the radiation environments (radiation conductors).
- An axi-symmetric model was used to simplify the model and allow modeling details required by the component-level assessments needed by the design team.
- The models were laid out to be easily reconfigurable via users constants (xk constants). The intent was to provide one model which could easily modified to assess many processing configurations and conditions.
- A detailed summary table was written to allow quick troubleshooting of the results and permit a quick generation and evaluation of results obtained at various set points.
- The radiation heat transfer was modeled using TRASYS with the system separated into three calculation domains to allow for greater model detail and fidelity and faster model turnaround.
- A hot zone test article was used to evaluate the modeling methodology and to verify thermal performance in a static test unit (non-translatable).
- The results obtained in the hot zone test article are applied to the design and analysis of the bread board unit and flight unit.
- The bread board model and correlated test data is used to provide inputs and correlated results to the flight unit.

QMI Thermal Analysis and Design Methodology



- The far left figure shows one of the three TRASYS models used to calculate the radiative heat transfer environment for QMI. This model is used to calculate internal bore-to-cartridge environments and external water jacket-to-ESA thermal chamber environments. The model is fully translatable to any 2mm location throughout the 20cm translation capability of the insert. The detailed modeling of the gradient zone is also shown in this figure.
- The middle figure shows the stationary portion of the three TRASYS models used for QMI. This model is used to obtain the heat transfer environment between the outer surface of the insulation jacket and the inner surface of the water jacket. This model also provides heat transfer environments on the guard end of the insert. The overimposed figure (as shown via animation during the presentation) shows how the two models work in conjunction with each other.
- The final figure is an animation denoting the ability of this approach to analyze any position within the 20cm translation capability of the insert by changing one of the many user defined variables in the translatable bore model. All of the TRASYS models were generated via user constants to enable the analysts to assess various cartridge configurations easily and quickly at any processing stage of the PIs processing profile.

QMI Thermal Analysis and Design Methodology



- The top/right figure shows a typical sample/cartridge temperature result plot. The processing conditions and assumptions used are denoted on the plot. Performance results (thermal gradient) and zone locations are shown.
- The middle lower figure shows a typical component-level temperature plot. The temperature of QMI components vs. their axial location is denoted in this figure. Once again, the processing conditions and assumptions used are denoted.
- The far right figure shows a typical summary table which is generated for every solved for processing condition. Component-level maximum, minimum, and average temperatures are provided. The summary plot is sub-divided into relevant levels to allow for easy overview of the conditions to which a given component is subjected.

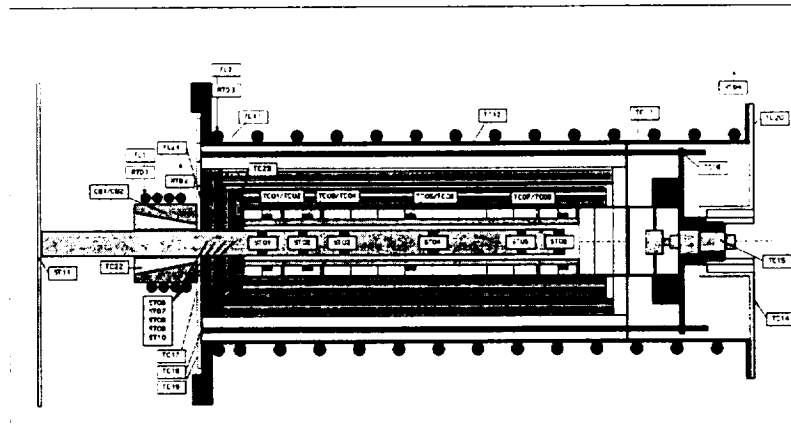
QMI Bread Board Testing and Instrumentation Approach

- *HZTA Testing focused on determination of insulation performance and verification of heat flow mapping (losses, contact coefficients)*
- *Bread Board focused on overall insert performance, chill block performance, hot zone control, and heat flow mapping*
 - *Furnace instrumentation placed to map the flow of heat from the heaters at various areas to obtain a total energy balance and evaluation of the system performance*
 - *Overall energy balance was obtained real-time by adding calculations to the data system for coolant loops to compare to power draw*
 - *Heat flow between components was verified by measuring temperature at the components know conductive heat flow paths*
 - *Detailed understanding of zone-to-zone interaction as a function of set points was required. Needed to assess what actual average bore temperature was obtained for a given zone's set point*
 - *Assess the ability to maximize the booster#1 set point temperature and maintain control of booster#2 to maximize gradient capability*

• Hot zone test article testing was used to provide assessments of the heat flow paths which existed within the QMI design. There were various interface contact conductances and/or heat transfer paths that had been assumed in the thermal model which needed to be verified. This static test setup was heavily instrumented to provide very good detail to the inner workings of the QMI design.

• Bread board testing was used to provide an assessment of the flight system in actual processing conditions. The testing has focused on obtaining accurate control of the heated zones and repeatable performance from the chill block along with some additional assessments of design modifications which have been performed since the hot zone test article testing.

QMI Bread Board Testing and Instrumentation Approach



- This figure denotes the instrumentation which was used for the bread board test setup.

- Thermocouple locations are denoted with a “TC##” label and RTD sensors are denoted with a “RTD#” label (CB1/CB2 are also RTDs).

- Probe instrumentation is shown with an “ST##” label.

- Flow meters are denoted with a “FL#” label.

- The positioning of these sensors was attained by a requirement to either: monitor a components temperature, determine the heat flow through a component, or obtain coolant loads.

- By using these instruments, an overall energy balance could be obtained by using the power supplies measured heat input (via current and voltage) and the coolant system’s coolant loads (using flow rate and temperature increase through a given component). This enabled the system to perform a heat flow path assessment and also determine when the overall system had truly reached a steady state condition.

- The use of the probe black bodies and the probe gradient zone readings allowed the hot zone set point accuracy and the cold zone performance to be assessed during testing. These readings also provided valuable information to check and debug the control system.

QMI Breadboard Thermal Probe Requirements

- *Provide repeatable and accurate measurements of furnace performance*
 - *Thermal gradient measurement*
 - *Surface properties*
 - *Material thermal conductivity*
 - *Gradient zone instrumentation location and spacing*
 - *Heated zone measurements*
 - *Surface properties*
 - *Heated zone instrumentation location*
 - *Instrumentation isolation*
- *Provide performance measurements while simulating a science sample*
 - *Heater power*
 - *Cold zone heat load*

•The intent of the thermal probe is to provide repeatable and accurate measurements of the furnace performance. The repeatability and accuracy of the measurements is limited to the life cycle and accuracy of the instrumentation.

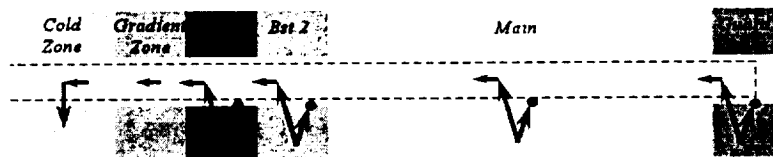
•Measurement of the thermal gradient in the probe ensures that the performance of the furnace is not degrading over time. The resulting measurement is dependant on the heat load into the probe and the heat transfer path through the gradient zone. The heat load into the probe is related to the probe surface properties, while the heat transfer path through the gradient zone is related to the material thermal conductivity and the spacing of the instrumentation.

•Measurement of the heated zone temperatures ensures that the heater control instrumentation is not decalibrated. The instrumentation should be isolated from the probe structure so as to measure the true heater temperatures.

•It is desirable to measure the gradient and heater zone performance while simulating a real science sample. The required heater power and heat load on the cold zone should be similar for the thermal probe and a science sample. Thus, the performance of the furnace is checked under a realistic processing environment.

QMI Thermal Probe Design Parameters

- | | |
|--|---|
| <ul style="list-style-type: none"> • <i>Surface properties</i> <ul style="list-style-type: none"> – High emissivity preferred – Stable under vacuum • <i>Materials selection</i> <ul style="list-style-type: none"> – Low thermal conductivity – 1400°C processing temperature | <ul style="list-style-type: none"> • <i>Instrumentation</i> <ul style="list-style-type: none"> – Location and spacing in the gradient zone – Location and isolation in the heated zone • <i>Science sample loading</i> |
|--|---|



•The thermal probe will be radiatively coupled to the heated zone. The heat rate into the probe is directly dependant on the probe's surface emissivity. Both the thermal probe and the science samples should have a high emissivity to maximize performance. The probe's surface properties should be resistant to oxidation and material reactions so that the coupling to the heated zone does not change over time. This will ensure that any degradations in measurements are associated with the furnace performance and not the probe performance.

•The probe's heat transfer path through the gradient zone is related to the thermal conductivity of the probe material. High conductivity materials will produce lower gradient readings as more heat is transferred through the gradient zone to the cold zone. Lower conductivity materials will result in higher gradient readings. The probe material should be able to survive the maximum furnace processing temperature of 1400°C. The material should be stable at the expected processing temperatures, requiring an inert material which will not react with other furnace materials.

•For gradient performance, the point of interest is along the centerline of the probe. The spacing of the instrumentation in the gradient zone will effect the accuracy of the readings. The accuracy will increase if the temperature difference between thermocouples is at its largest; therefore, the spacing should be minimized. The accuracy will also increase with a lower conductivity material.

•For heated zone performance, measurements should be taken in each of the four zones. Multiple measurements should be taken in the longer main heater zone. The instrumentation needs to be well coupled to the heater and isolated as much as possible from the thermal probe so that the measurements are of the heaters and not the probe. The instrumentation also needs to be well coupled to

Preliminary Thermal Probe Designs

- *High Gradient Furnace with Quench (HGFQ)*
 - 1.6cm OD stainless steel probe
 - Performance at 1100 °C processing
 - 169 - 218 °C/cm gradient
 - 1100W steady state heater power (inert gas furnace)
- *Hot Zone Test Article (HZTA)*
 - 1.6cm OD stainless steel probe
 - Performance at 1200/1150/1100/1100°C processing
 - 182°C/cm gradient
 - 342W steady state heater power
- *QMI PDR Probe Design*
 - 1.3cm OD aluminum nitride probe
 - Performance at 1200/1150/1100/1100°C processing
 - 132°C/cm gradient
 - 298W steady state heater power

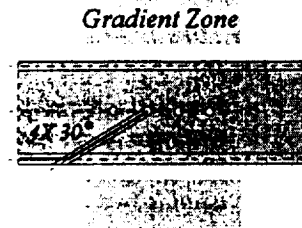
•Preliminary thermal probe designs used for HGFQ and HZTA were made of stainless steel. Their function was to measure gradient performance. The maximum processing temperature for these furnaces was 1200°C, making stainless steel a feasible choice. Due to the relatively low thermal conductivity of the stainless steel, gradients above 200 °C/cm were attainable.

•Stainless steel has a melt temperature of 1397 °C. A new probe material was needed to withstand the 1400 °C processing temperatures of QMI. In addition, the stainless steel surface properties would possibly change over time producing variable results.

•At PDR timeframe, the QMI thermal probe function was to measure gradient performance. An aluminum nitride probe material was selected due to its high melt temperature of 2227 °C. The aluminum nitride also has an emissivity higher than stainless steel ($\epsilon = 0.6$ verses $\epsilon = 0.2$); however, the thermal conductivity is five and a half times that of stainless steel. The resulting gradient measurements were significantly lower than the stainless steel probe measurements.

Design Features for Gradient Measurement

- *1.6cm solid tantalum thermal probe*
 - *Surface emissivity of 0.2*
 - *Low thermal conductivity of 2.8 Btu/hr in °F*
- *Four Type C tantalum sheath thermocouples*
 - *Thermocouple spacing of 0.3 in*
 - *Sheaths run along surface grooves*
- *Beads positioned at probe centerline with a 30° entry angle*
- *Beads potted into position with epoxy*

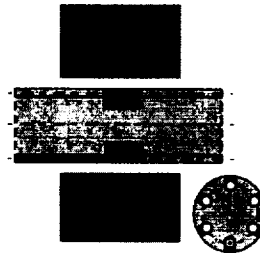


•Tantalum was chosen as the QMI breadboard thermal probe material. The melt temperature of tantalum is 2996 °C making it acceptable for the 1400 °C processing temperatures. The emissivity of bare tantalum is 0.2. The original plan was to apply a high emissivity coating to the tantalum such as silicon carbide ($\epsilon = 0.9$). Time constraints required that the bare tantalum probe be used for breadboard testing. The thermal conductivity of tantalum is two and a half times that of stainless steel resulting in slightly lower gradients than a stainless steel probe would offer. The tantalum is also twice as dense as stainless steel making it a significantly heavier probe.

•Gradient measurements were made by four thermocouples spaced equally along the 1.0 inch long gradient zone. The four thermocouples were equally spaced to facilitate gradient calculations and to maximize thermocouple accuracy. So as not to disturb the Veltherm interface at the cold zone, the thermocouples run along surface grooves. It was desirable that the thermocouple sheath material be the same as the probe material so that alloying reactions did not occur. The thermocouples were taken from the probe surface grooves to the probe centerline at a 30° entry angle to minimize bending. The thermocouple beads were potted into place with epoxy.

Design Features for Heated Zone Measurements

- *Graphite ring black body sensors*
 - *Surface emissivity of 0.9*
 - *Maximize heat transfer to sensors without compromising heat transfer to probe*
- *Sensors isolated from probe*
 - *Dimpled tantalum shields wrapped to cut radial losses*
 - *Multiple tantalum disks cut axial losses*
- *Type C tantalum sheath thermocouples*
 - *Sheaths run along surface grooves*
 - *Beads potted into graphite rings with epoxy*

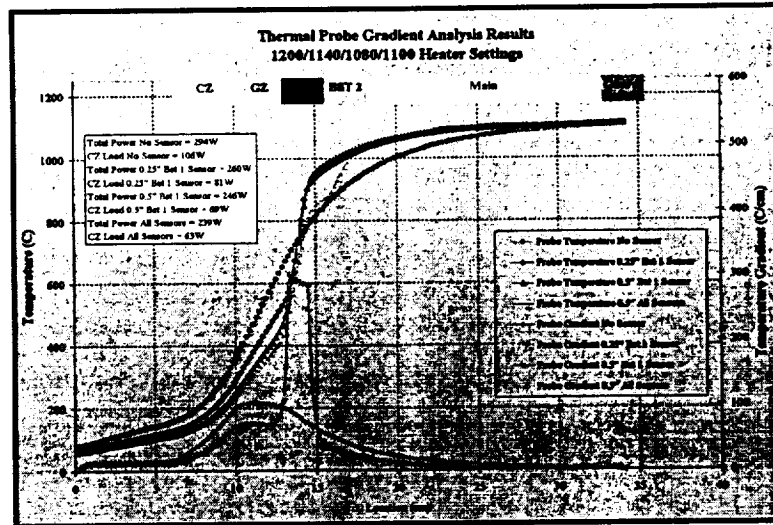


•The heated zone measurement sensors were made from graphite rings. The graphite emissivity of 0.9 provided the necessary coupling of the sensor to the heater zone. The surface area of the sensors was balanced so as to maximize the radiative couple to the heated zone without compromising the radiative couple between the thermal probe and the heated zone.

•The sensors were isolated from the thermal probe structure with dimpled tantalum shields wrapped several times around the probe in the radial direction. Tantalum was chosen for the shields to eliminate any alloying reactions. Axial losses were minimized with multiple tantalum disks on either side of the sensors.

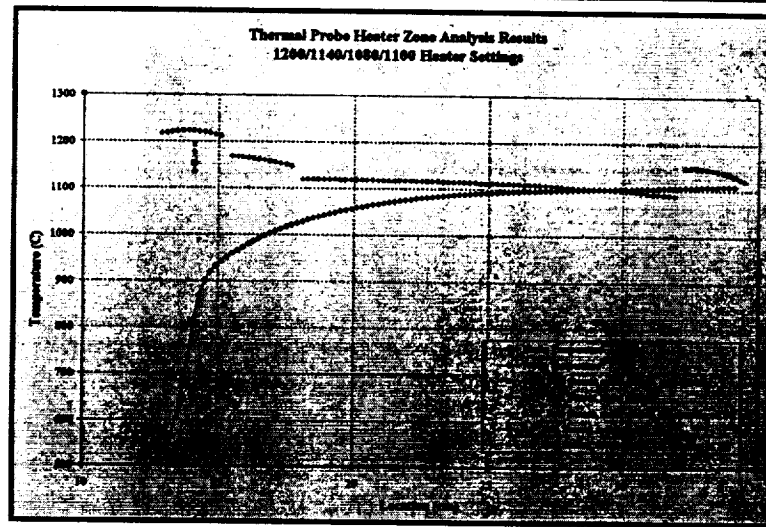
•The sensor thermocouples were run along the probe in surface grooves. The thermocouple beads were potted into the graphite rings with graphite epoxy.

Thermal Gradient Analysis Results



- The primary purpose of the gradient analysis was to verify that the probe design allowed heat to be transferred to the probe structure and through the gradient zone in a manner similar to a science sample. This included balancing the blackbody sensor ring cutouts with the resulting heat transfer to the gradient zone.
- The above slide shows the results of this analysis.
- The analysis was performed with heater set points corresponding to science sample processing. The booster 1, booster 2, main, and guard set points were 1200, 1140, 1080, and 1100°C respectively.
- As a baseline case, the thermal probe design was analyzed without the blackbody sensors and corresponding cutouts. The resulting gradient was 103 °C/cm. This was considered the highest gradient achievable with the given probe and heater set point temperatures. Through breadboard model correlation activities (discussed later), it was discovered that the actual surface emissivity of the thermal probe was around 0.7. This would result in higher gradient measurements.
- The gradient corresponding to a 0.25 inch cutout/sensor in the booster 1 zone is 83 °C/cm. For a 0.5 inch cutout/sensor in the booster 1 zone, the gradient prediction is 71 °C/cm. A 0.5 inch cutout/sensor at all six locations along the heated zone results in a gradient of 65 °C/cm. Note that the higher gradients indicated in the heated zone are due to the thermal probe cutouts choking of the heat flow. Shunting of the thermocouples by the cold zone was not an issue due to the significant coupling of the thermocouple to the probe structure.

Heated Zone Analysis Results



- The purpose of the heated zone analysis was to isolate the blackbody sensors from the probe so that the measurements are of the heaters, not the probe. The above slide shows the temperature profiles of the thermal probe and the heated zone. As seen in the slide, the largest temperature difference in the probe and heaters occurs in booster 1 with the average booster 1 bore temperature being 1219 °C and the probe temperature in that zone being 528 to 943 °C. Isolation parametrics were therefore performed on the booster 1 sensor.

- For a 0.25 inch sensor with shielding in the radial and axial directions, the sensor temperature was 1193 °C . With shielding only in the radial direction, the sensor temperature was 1153 °C . The sensor temperature was further reduced when taking into account the heat leak from the thermocouple to the cold zone. The shunting of the thermocouple results in a sensor temperature of 1139 °C .

- For a 0.5 inch sensor with shielding in the radial direction, the sensor temperature is 1178 °C . The shunting of the thermocouple to the cold zone brings the sensor temperature down to 1169 °C .

Breadboard Thermal Probe Layout

- *Four centerline thermocouples in gradient zone*
- *Six isolated 0.25 inch blackbody sensors in heated zones*
 - *One sensor in Bst1, Bst2, and guard and three sensors in longer main*
 - *One thermocouple per sensor*



- The final breadboard probe layout is shown in the above slide. The outer diameter of the probe is 1.55cm (0.61in) after straightening. The total probe length is 15 inches including the portion of the probe mounted in the head.
- The four centerline thermocouples for gradient measurement are positioned in the gradient zone when the probe is fully inserted into the QMI furnace.
- The 0.25 inch blackbody sensors were centered in each of the heated zones with three sensors in the longer main zone. Each sensor was equipped with one thermocouple for a total of six measurements over the four zones.

Flight Thermal Probe Requirements

- *Provide repeatable and accurate measurements of heated zone*
 - *Blackbody sensor design concept*
 - *Limited to 12 thermocouples by MSL*
- *Incorporate MSL required safety thermocouple*
- *Maximize probe life*
 - *Eliminate gradient measurement*
 - *Cold zone performance monitored by PT1000s*
- *Minimize weight*
 - *Decrease use of tantalum material*

•The requirements for the flight probe differ somewhat from the breadboard probe requirements. The flight probe will be designed to only measure the heated zone performance. The blackbody sensor design will be incorporated for these measurements.

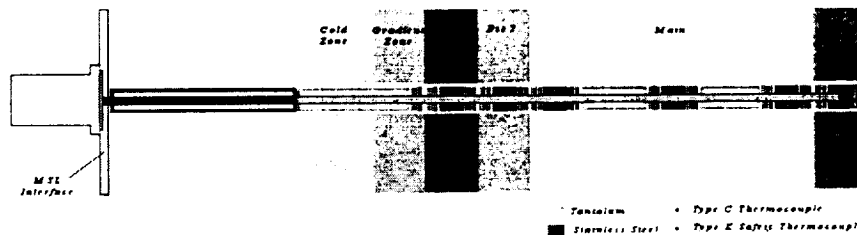
•The MSL interface will allow for a total of twelve thermocouples. MSL requires the thermal probe to contain one Type K thermocouple for touch temperature measurement. This leaves 11 thermocouples for heated zone temperature measurement.

•In order to maximize the life of the flight probe, the gradient zone measurements have been eliminated. In order for these measurements to be valid, the probe must be coupled to the cold zone. Since the cold zone Veltherm coupling is located on each of the probes or samples, the interface performance can not be verified from the probe alone. In addition, the veltherm has a limited life as insertion, removal, and translation cause wear. Eliminating the Veltherm interface extends the life of the probe. The two PT1000s to be place in the outer sleeve of the cold zone will be used to monitor its performance.

•The final requirement for flight is to minimize the weight of the probe. Although the tantalum withstands the QMI processing environment, the tantalum is a high density metal. It is therefore desirable to reduce the amount of tantalum material wherever temperatures allow.

Flight Thermal Probe Design Features

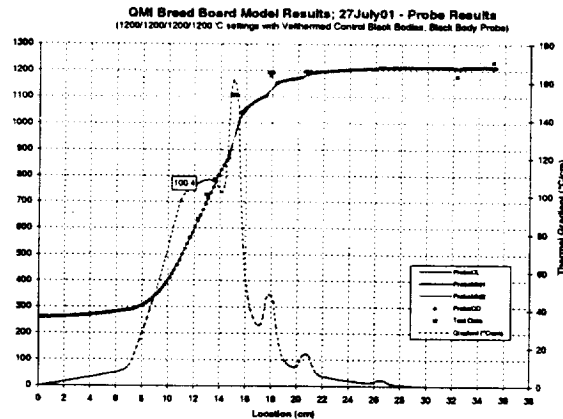
- *Six 0.5 inch blackbody sensors in heated zones*
 - *Graphite or silicon carbide coated boron nitride rings*
 - *Redundant thermocouples in each sensor except main central sensor*
 - *Sensors isolated from one another by axial shielding*
- *Weight reduction*
 - *Tantalum shaft with thin walled tantalum brackets*
 - *Substitution of stainless steel where temperatures allow*



•The 0.5 inch black body sensor design has been chosen for the flight probe since gradient measurement is no longer needed. The graphite material may be replaced with boron nitride in order to increase the fracture resistance and corrosion resistance of the sensors. The boron nitride will need a high emissivity coating to maximize the coupling to the heated zone. Having eleven thermocouples available means that redundant measurements can be taken in each sensor with the exception of the main central sensor. The axial losses will be reduced with multiple shields on either side of the sensors.

•It is desirable for the probe outer geometry to be similar to the science sample geometry; however, the weight of the tantalum needs to be reduced. To accommodate this, the sensors and shields will be supported by a tantalum shaft. Thin walled tantalum brackets will then be used to create a uniform outer diameter. In addition, stainless steel will be used on the cool side of the cold zone since the processing temperatures in this area are well within the limitations of the material.

QMI Bread Board Correlation and Performance

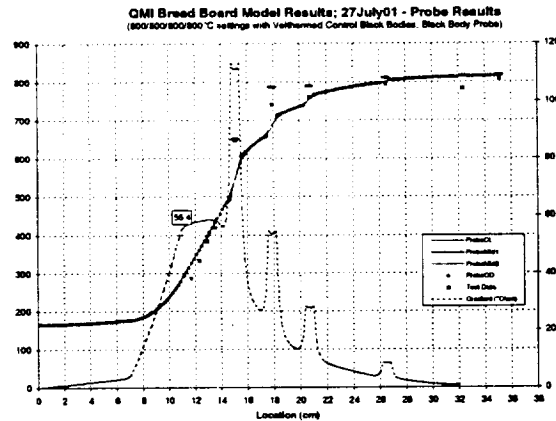


- This figure shows a comparison of test data obtained from a 1200°C uniform bore set point case which was performed on 27July01 and the current model correlation result.

- This data shows that the correlated model agrees very well with the test data. Gradient zone temperatures are very close in agreement. Zone set points are very close in agreement, but the test data does show that the guard heater is being slightly overran (higher than 1200°C) which is causing the main heater to be underun (set point lower than 1200°C). This has been found to be due to the inherent heat leak associated with the thermocouple instrumentation layout. The guard zone control thermocouple has the shortest sheath length to the sheath/lead wire transition. Therefore, it is affected by cooling at the transition's location.

- It was determined from this correlation, that there was a substantial amount of thermal coupling of the booster#1 probe black body with the probe structure. This is assumed to be caused by the substantially different temperatures found at this axial location. The booster#1 black body is at a temperature of about 1100°C while the probe structure is at a temp of 950°C for the same axial station. This difference in temperature would cause the black body to elongate more than the groove in which it is contained (probe structure). This thermal expansion difference would cause a coupling due to contact pressure between the black body and the probe structure.

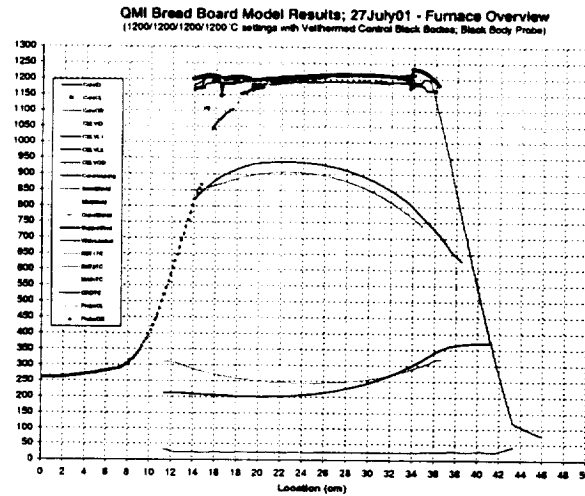
QMI Bread Board Correlation and Performance



- This figure shows a comparison of test data obtained from a 800°C uniform bore set point case which was performed on 27July01 and the current model correlation result.

- This data shows that the correlated model doesn't agree as well as the previously shown high temperature data (1200°C). Gradient zone temperatures are close, but not in as good agreement as the higher temperature results. Zone set points are also somewhat in agreement. This is an initial correlation comparison. Further testing and debugging of the model and control system is currently underway to attain a better result.

QMI Bread Board Correlation and Performance



- This figure shows a component-level plot of the analytical results obtained from the 1200°C uniform bore set point case which was performed on 27July01.
- This data is useful for assessing the test results with respect to the monitored temperature locations. Using the summary table and this axial plot, the temperature variations, gradients, and max. temperature location for a given component can be ascertained.

QMI Bread Board Correlation and Performance

- This table shows an overall comparison of test data obtained from various uniform bore set point cases and the current model correlation result.
- This data shows that the correlated model agrees fairly well, but does need some additional tuning. The power requirements are relatively close in agreement, but are still being reviewed and updated.
- A post test evaluation of the control instrumentation has shown that the thermocouples used in this test were not properly manufactured. The vendor did not use the correct lead wire materials resulting in the formation of an additional bead at the sheath-to-lead wire transition. This manufacturing defect resulted in a loss of accuracy caused by heating of the transitions. A workaround of monitoring the transition temperatures has provided a temporary alleviation of the problem and additional testing is planned. The correlation will be updated when this new test data becomes available.

Summary and Conclusions

- QMI bread board testing in conjunction with the model modeling has proved invaluable to design verification.

Problems of furnace operation were identified and corrected through the use of the model and furnace probe positioning.

Thermal probe that failed to respond was identified and replaced, resulting in improved control system.

A simplified SACA type test piece has been prepared to produce inserts at 900°C in the model and inserts made of 11.7mm diameter alumina crucible to sample 1000°C processing temperature.

- QMI bread board is providing invaluable information on the capabilities and evaluation of the design.
- Results obtained and lessons learned from bread board testing are being incorporated into the QMI flight design.
- Current bread board activities include retooling the control instrumentation for near term testing which will include furnace

•This paper has shown the importance of proper bread board and developmental testing used in conjunction with thermal modeling. In areas of uncertainty, benchtop testing or system level testing used in conjunction with thermal modeling can provide insight into the detailed performance of a design unit. The areas in which the thermal model and test instrumentation has been shown to be invaluable is in the verification of performance, verification of operating procedures, verification of installation and assembly of the system, and characterization of the control system (both hardware and software).

•The model has been used to identify an improper initial furnace location of 5-8mm.

•The model has also been useful to troubleshoot the control instrumentation.

•A preliminary test of a simplified SACA design has shown that QMI can attain acceptable thermal gradients in a sample diameter larger than the PIs' requirement of 10mm. This test used a 11.7mm diameter sample in conjunction with a 900°C sample processing temperature and thick-walled alumina crucible to conservatively determine the insert's capability to meet the 100°C/cm gradient requirement.

•This paper presented an overview of how the test data is used to correlate analytical models.

•Lessons learned are passed up to the flight models to insure a more accurate prediction of the flight insert's capabilities.

•The current status of the bread board is a redesign of the control instrumentation. The previous design was found to be inadequately coupled via test data and thermal model results. This redesign was brought about by the bread board correlation effort. A manufacturing defect in the thermocouple design was also determined during this effort.